Why are massive O-rich AGB stars in our Galaxy not S-stars?

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Abstract. We present the main results derived from a chemical analysis carried out on a large sample of galactic O-rich AGB stars using high resolution optical spectroscopy (R∼40,000–50,000) with the intention of studying their lithium abundances and/or possible s-process element enrichment. Our chemical analysis shows that some stars are lithium overabundant while others are not. The observed lithium overabundances are interpreted as a clear signature of the activation of the so-called "Hot Bottom Burning" (HBB) process in massive galactic O-rich AGB stars, as predicted by the models. However, these stars do not show the zirconium enhancement (taken as a representative for the s-process element enrichment) associated to the 3rd dredge-up phase following thermal pulses. Our results suggest that the more massive O-rich AGB stars in our Galaxy behave differently from those in the Magellanic Clouds, which are both Li- and s-process-rich (S-type stars). Reasons for this unexpected result are discussed. We conclude that metallicity is probably the main responsible for the differences observed and suggest that it may play a more important role than generally assumed in the chemical evolution of AGB stars.

INTRODUCTION

The Asymptotic Giant Branch (AGB) is formed by stars with initial masses in the range between 0.8 and 8 M$_\odot$ in a late stage of their evolution. During most of the time H burning is the main source of energy for the AGB star but, occasionally, the inner He shell ignites in a "thermal pulse" and, eventually, the byproducts of He burning may reach the outer layers of the atmosphere (the so-called 3rd dredge-up). Thus, AGB stars, originally O-rich, can turn into C-rich AGB stars (C/O > 1) after a few thermal pulses. Another important characteristic of AGB stars is the presence of neutron-rich elements (s-elements like Rb, Zr, Ba, Tc, Nd, etc.) in their atmospheres which are the consequence of the slow-neutron captures produced during the thermal pulsing phase. According to the most recent models two major neutron sources can operate in AGB stars depending on the stellar mass. The $^{13}C(\alpha,n)^{16}O$ reaction is the preferred neutron source for masses around 1−3 M$_\odot$ while for intermediate mass stars (M > 3 M$_\odot$) the neutrons are thought to be mainly released by $^{22}Ne(\alpha,n)^{25}Mg$ (see e.g. Lattanzio & Lugaro 2005 for a recent review).

In the case of the more massive O-rich AGB stars (M > 4 M$_\odot$), the convective envelope can penetrate the H-burning shell activating the so-called "Hot bottom burning" (HBB) process. HBB takes place when the temperature at the base of the convective envelope is hot enough (T $\geq 2\times10^7$ K) and ^{12}C can be converted into ^{13}C and ^{14}N through the CN cycle (Sackmann & Boothroyd 1992). HBB models (e.g. Mazzitelli, D'Antona & Ventura 1999, hereafter MDV99) predict also the production of ^7Li by the chain $^3He(\alpha,\gamma)^7Be$ (e$^-$,v)^7Li, through the so-called "^7Be transport mechanism" (Cameron & Fowler 1971). One of the predictions of these models is that Li should be detectable, at least for some time, on the stellar surface.

The HBB activation in massive O-rich AGB stars is supported by studies of AGB stars in the Magellanic Clouds (hereafter, MCs) (e.g. Plez, Smith & Lambert 1993). The detection of strong Li overabundances together with strong s-element enhancement in these massive (and luminous) AGB stars is the signature that they are indeed HBB stars which have undergone a series of thermal pulses and dredge-up episodes in their recent past.

In our own Galaxy, only a handful of Li-rich stars have been found so far (e.g. Abia et al. 1993). Most of them are low mass C-rich AGB stars (e.g. Abia & Isern 2000) and intermediate mass S- and SC-stars (e.g. Abia

& Wallerstein 1998) and not O-rich M-type stars. However, HBB is expected to be active in the most massive (and luminous) AGB stars (from $\sim$4 to 7 M$_\odot$ according to MDV99 HBB models), which might not be C-rich, but O-rich. The best candidates are the so-called *OH/IR stars*, luminous O-rich AGB stars extremely bright in the infrared, showing a characteristic double-peaked OH maser emission at 1612 MHz. These stars are also known to be very long period variables (LPVs), sometimes with periods of more than 500 days and large amplitudes of up to 2 bolometric magnitudes. However, they experience very strong mass loss rates (up to several times 10^{-5} M$_\odot$yr^{-1}) and most of them are usually heavily obscured at this stage by thick circumstellar envelopes, making optical observations very difficult. Thus, no information exists yet on their Li abundances and/or possible s-process element enrichment.

OBSERVATIONS AND RESULTS

A large sample (102) of long-period (300−1000 days), large amplitude variability (up to 8−10 magnitudes in the V band), late-type (> M5) O-rich AGB stars displaying OH maser emission with a wide range of expansion velocities (from just a few km s^{-1} to more than 20 km s^{-1}) was carefully selected. Stars were included in the sample if satisfying at least one of the above criteria and ideally as many of them as possible, which guarantees that they are actually massive stars. Consistently, stars in the sample were mainly members of the galactic disk population and displayed strong IR excesses detected by IRAS.

High-resolution optical echelle spectra (R$\sim$40,000–50,000) were obtained for all stars in the sample during several observing periods in 1996–1997. The full log of the spectroscopic observations is shown in Table 1, including more detailed information on the observations. The two-dimensional frames containing the echelle spectra were reduced to single-order one-dimensional spectra using the standard ECHELLE software package as implemented in IRAF[1]. Because of the very red colours of the sources observed, the S/N ratios achieved in the reduced spectra can strongly vary from the blue to the red orders (10-20 at $\sim$6000 Å while >100 at $\sim$8000 Å).

We detected the presence of the Li I resonance line at 6708 Å in 25% of the sources in the sample with a wide variety of strengths, while we did not find any signature of this line in 31% of the stars. The remaining 44% were

[1] Image Reduction and Analysis Facility (IRAF) software is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
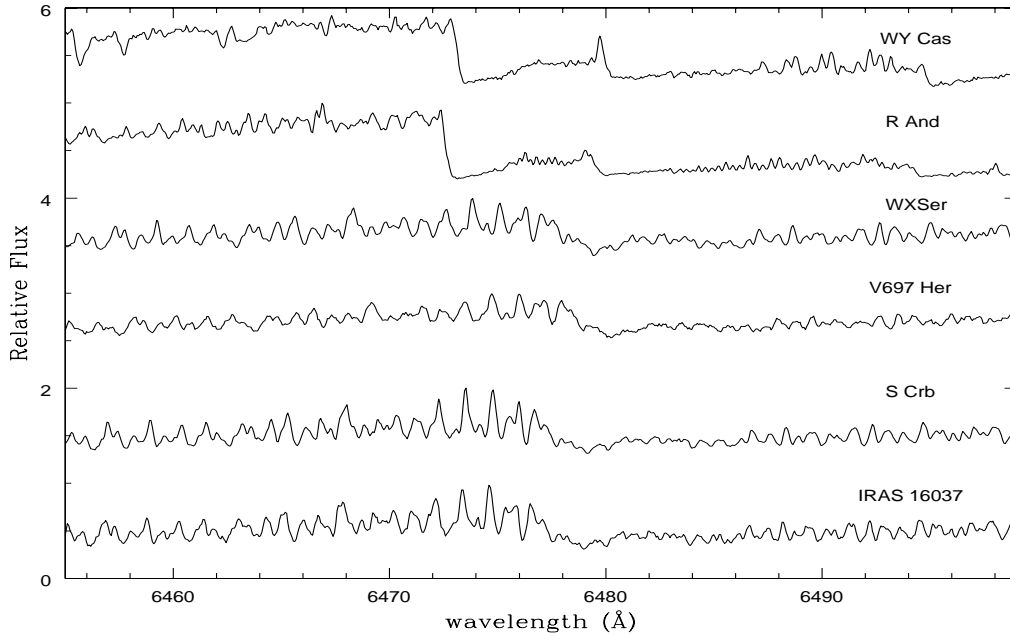
TABLE 1. Log of the spectroscopic observations

Set-up	Date	$\Delta\lambda$ (Å/pix)	Range (Å)
4.2m WHT/UES	August 1996	0.065	5300-9400
4.2m WHT/UES	June 1997	0.065	4700-10300
4.2m WHT/UES	August 1997	0.065	4700-10300
3.6m ESO/CASPEC	February 1997	0.085	6000-8200

heavily obscured by their thick circumstellar envelopes and they were too red/not found at optical wavelengths. In general, all stars (with or without lithium) show extremely red spectra with the flux level falling dramatically at wavelengths shorter than 6000 Å. In addition, the spectra are severely dominated by strong molecular bands mainly due to titanium oxide (TiO), as a consequence of the very low temperature and the O-rich nature of these stars. Interestingly, the bandheads of ZrO seem to be absent in all spectra. This is shown in Figure 1 where we show the spectral region around the ZrO bandheads at 6474 and 6495 Å. These ZrO bandheads (as well as those corresponding to other s-element oxides such as LaO or YO) are very strong in galactic S-stars and in massive MC AGB stars.

CHEMICAL ANALYSIS

Our analysis combines state-of-the-art line blanketed model atmospheres and synthetic spectroscopy with extensive linelists. We have used the spherically symmetric, LTE, hydrostatic 'MARCS' model atmospheres for cool stars and the 'TURBOSPECTRUM' spectral synthesis code (Alvarez & Plez 1998) to derive the Li and Zr (taken as representative of all other s-process elements) abundances in those stars for which an optical spectrum could be obtained.

From an exhaustive study of the influence of the variations of the fundamental stellar parameters (*e.g. T_{eff}, log g, M, z, ξ, C/O, etc.*) on the synthetic spectra and from our knowledge of the main characteristics of our stars we obtained the most adequate initial set of parameters as well as their plausible range of variation, and we constructed a grid of MARCS model spectra.

Thus, we first determined by χ^2 minimisation which of the spectra from our grid of models provided the best fit to the observations in the 6670−6730 Å and the 6455−6499 Å spectral regions. The goal was to fit the overall shape of the spectra including the TiO bandheads, which are very sensitive to variations in the effective temperature. Then, the Li and Zr abundances were derived by fitting the Li I resonance line at $\sim$6708 Å and the ZrO molecular bands at 6474 Å and 6495 Å, respectively. As an example, the best fit in the 6670−6730 Å spectral re-

FIGURE 1. High resolution optical spectra of sample stars displaying the lack of the ZrO absorption bands at 6474 and 6495 Å compared with two galactic S-stars (WY Cas and R And). WX Ser (IRAS 15255+1944) and V697 Her (IRAS 16260+3454) are Li-detected while S CrB (IRAS 15193+3132) and IRAS 16037+4218 are Li non-detected. The absorption band at ∼6480 Å corresponds to the TiO molecule.

gion around the Li I line is presented in Figure 2 for the star IRAS 11081−4203.

LI AND ZR ABUNDANCES

Our chemical abundance analysis shows that half of the stars show Li overabundances in the range *log ε(Li)*∼0.5 and 3.0[2]. A very similar range of Li overabundances is found in the massive O-rich AGB stars studied in the MCs (e.g. Plez, Smith & Lambert 1993). The Li overabundances observed are interpreted as a signature of the activation of the so-called "Hot Bottom Burning" (HBB), confirming that they are massive AGB stars (M > 4 M$_\odot$ according to MDV99 HBB models).

However, the non-detection of the ZrO molecular bands at 6474 Å and 6495 Å in any of the stars analysed imposed severe upper limits to the zirconium abundance ([Zr/Fe]<0.0−0.25 for $T_{eff} \geq$ 3000 K and [Zr/Fe]<0.25−0.50 for $T_{eff} <$ 3000 K). If the Zr enhancement is taken as a representative for the s-process

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[2] Li abundance in the scale 12+*log N(Li)*. Note that the uncertainty in the Li abundances derived is estimated to be of the order of 0.4−0.6 dex. This error reflects mostly the sensitivity of the derived abundances to changes in the atmospheric parameters taken for the modelling.
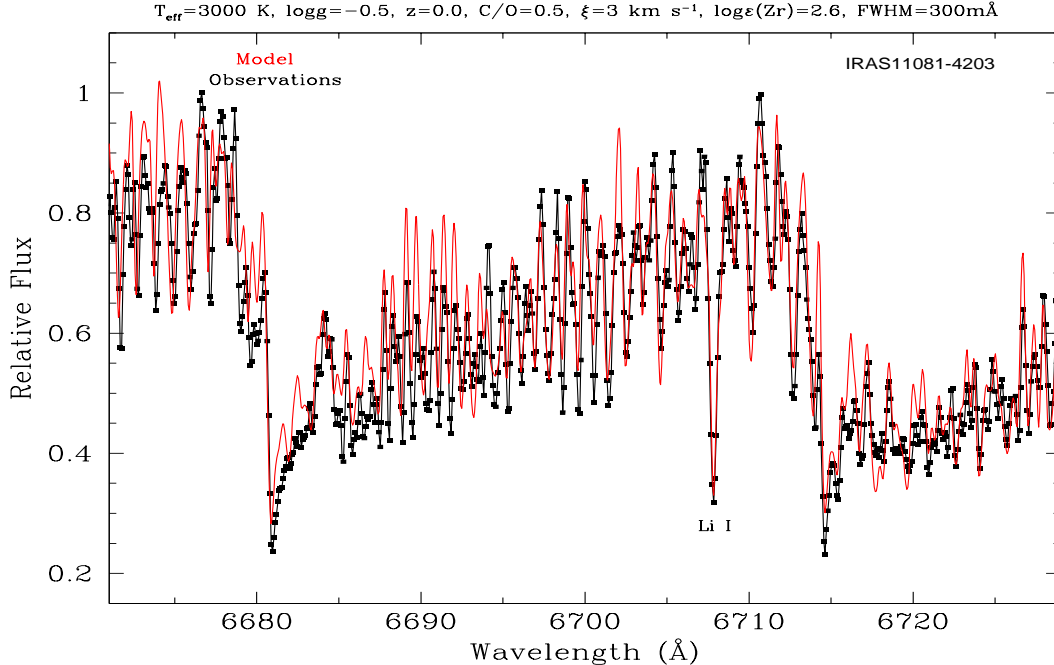
enrichment, our results indicate that the massive AGB stars in our Galaxy are not S-stars.

COMPARISON WITH THE MAGELLANIC CLOUDS

In contrast with their galactic analogues, the more massive AGB stars in the MCs are O-rich stars showing s-process elements enhancement (S-stars). In addition, a higher proportion of them (∼80% compared to ∼50% in our Galaxy) shows also Li enhancement. The Li enhancement indicates that they are also HBB stars but, why are these stars also enriched in s-process elements?

The answer to this question must be related to the different metallicity of the stars in the MCs with respect to our Galaxy. Actually, theoretical models predict a higher efficiency of the dredge-up in low metallicity atmospheres (e.g. Herwig 2004) with respect to those with solar metallicity (e.g. Lugaro et al. 2003).

In addition, there is an increasing observational evidence that lower metallicity environments are also less favourable to dust production, as it is suggested by the very small number of heavily obscured AGB stars in the MCs (e.g. Groenewegen et al. 2000). This is supported by the lower dust-to-gas ratios derived by van Loon

T_{eff}=3000 K, logg=−0.5, z=0.0, C/O=0.5, ξ=3 km s^{-1}, logε(Zr)=2.6, FWHM=300mÅ

FIGURE 2. Best model fit and observed spectrum in the region 6670−6730 Å for the star IRAS 11081−4203. The T_{eff} and Li abundance derived from this spectrum was 3000 K and *log ε(Li)*=1.3, respectively. The parameters of the best model atmosphere fit are indicated in the top label.

(2000) in the few obscured MC AGB stars for which this analysis has been made. If mass loss is driven by radiation pressure on the dust grains, this might be less efficient with decreasing metallicity (Willson 2000). In that case, longer AGB lifetimes would be expected, which could increase the chance of nuclear-processed material to reach the stellar surface. The slow evolution predicted for AGB stars in the MCs as a consequence of the less efficient mass loss leaves time for more thermal pulses to occur during the AGB lifetime and, therefore, a more effective dredge-up of s-process elements to the surface can be expected before the envelope is completely gone at the end of the AGB. This would explain why even the more massive stars in the MCs show a strong s-process enrichment in contrast to their galactic counterparts. In our Galaxy the only AGB stars showing a similar over-abundance in s-process elements seem to be the result of the evolution of low- to intermediate-mass stars (M < 1.5−2.0 M$_\odot$), while no or very litle s-process enhancement is observed in galactic AGB stars with higher main sequence masses.

Finally, the lower critical mass needed to develop HBB (e.g. M > 3 M$_\odot$ at the metallicity of the LMC, compared to the ∼4 M$_\odot$ limit in our Galaxy) would favour the simultaneous detection of s-process elements and Li enrichment in a larger number of AGB stars in the MCs, as it is actually observed. In contrast to their MC counterparts, Li-rich massive AGB stars in our Galaxy would evolve so rapidly (because of the strong mass loss) that there is no time for a significant enhancement in s-process elements.

In summary, our results suggest that the dramatically different abundance pattern found in AGB stars belonging to the MCs and to our Galaxy can be explained in terms of the different metallicity conditions under which these stars evolved. This is the first observatinal evidence that the chemical evolution during the AGB could be strongly modulated by metallicity. A complete description and discussion of these results as well as their evolutionary consequences will be given in García-Hernández et al. (2005, in preparation).

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